ONR Graduate Traineeship Award in Ocean Acoustics for Mr. Joshua D. Wilson

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LONG-TERM GOALS:

The goal of this research is to test the hypothesis that inexpensive underwater acoustic measurements can be used to determine the wind speed and classify the destructive power of a hurricane with greater accuracy than standard satellite remote sensing techniques. It is proposed to do this by conducting field experiments in cooperation with the Mexican Navy just off the Mexican Isla Socorro which has a well-equipped meteorological station and the highest frequency of tropical cyclone occurrences in the world [6].

While current satellite technology has made it possible to effectively detect and track hurricanes, expensive `hurricane-hunting' aircraft are required to accurately classify their destructive power. Because of their expense, the United States only routinely deploys these aircraft over the North Atlantic and Gulf of Mexico [6,5] leaving vast areas with interest to national security, including the entire Pacific Ocean, uncovered.

Current experimental and theoretical evidence suggests that inexpensive underwater acoustic sensors may be used to accurately classify the destructive power of a hurricane. In 1999 an autonomous underwater acoustic sensor deployed by NOAA in the North Atlantic recorded the underwater noise as hurricane Gert passed overhead. By correlating this noise with meteorological data from reconnaissance aircraft and satellites we show that low frequency underwater noise intensity is approximately proportional to the cube of the local wind speed. Our analysis shows that it should be possible to estimate hurricane wind speed to an accuracy similar to that of specialized `hurricane hunting' aircraft [5] using underwater acoustic sensors, and from this accurately classify the destructive power of the hurricane.

To give some background, the 1970 Bangladesh hurricane killed over 300,000 people [6] and in 1992 hurricane Andrew caused over 25 billion dollars in damage [6,11]. The United States Commission on Ocean Policy has emphasized the need for accurate classification of hurricane destructive power to improve disaster planning [11]. For example, inaccurate classification can lead to poor forecasting and

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unnecessary evacuations, which are costly, or missed evacuations, which can result in loss of life [3]. Current classification and warning systems save an average $2.5 billion each year in the United States alone [11] and more accurate classifications systems could save even more.

OBJECTIVES:

The objective of this research is to accurately measure the wind speeds and so accurately classify the destructive power of a hurricane using underwater acoustic techniques. This work includes (1) analyzing existing underwater acoustic measurements of hurricane noise and correlating those measurements with the hurricane's wind speed and power, (2) conducting field experiments, in cooperation with the Mexican Navy, to further explore the relationship between hurricane winds and underwater noise, and (3) developing theoretical models for the propagation of hurricane sound through ocean waveguides and its measurement by hydrophones and hydrophone arrays.

APPROACH:

We have experimentally and theoretically demonstrated the potential accuracy of hurricane wind speed measurements using underwater acoustics, however, the empirical relationship between hurricane noise and wind speed is not yet definitive (see next section). We propose a field experiment to test our hypothesis that underwater acoustics can be used to accurately determine the wind speeds and classify the destructive power of a hurricane or tropical cyclone. To do this we will make repeated concurrent measurements of wind speed and underwater noise intensity during the passage of tropical cyclones.

In cooperation with Jose Vazquez of ONR Global Latin America we have obtained the support and approval of Admiral Peyrot and Vice Admiral Narro of the Mexican Navy's office of Science and Technology to deploy an autonomous acoustic sensor package off the coast of Mexico's Isla Socorro and conduct the necessary experiment to test our hypothesis. Isla Socorro provides a unique environment for our experiment since it lies in the region of the world most frequented by hurricanes, it already has established meteorological facilities, and it provides an ideal near shore location for deploying an underwater hydrophone. This region has been frequently used for other hurricane research 2]. Using the existing meteorological facilities and our own acoustic sensor package, we will make concurrent hydrophone and anemometer measurements that will enable us to correlate underwater noise with wind speed and test our hypothesis.

To make the underwater acoustic measurements a small sensor package will be deployed underwater off the coast of Isla Socorro. This senor package has been successfully used by Cato and McCauley to inexpensively measure biologically and meteorologically generated noise off the coast of Australia. Also by deploying the mooring at a depth of at least 100 m they have shown that the sensor package can survive severe weather conditions. The sensor package consists of a recording system connected to a hydrophone which is anchored to the sea floor. A sub-surface buoy and an acoustic release system make the system recoverable.

The recording system, built by the Curtin Centre for Marine Science and Technology, consists of a 6 kHz 16 bit analog to digital converter, a 16 GB hard drive and a battery pack. By recording at intermittently, this system is capable of measuring the underwater sound for months during the hurricane season. On average the island of Socorro experiences three hurricanes each season. This gives us the opportunity to deploy the sensor package for several months and potentially record data from multiple hurricanes. In addition to the underwater acoustic measurements, we will make

concurrent wind speed measurements. These wind speed measurements will be made with anemometers based on Isla Socorro.

One important aspect of the current proposal is to insure that concurrent and repeated measurements of underwater sound and hurricane wind speed are acquired and analyzed. A fixed bottom-moored acoustic sensor package located deep enough to be sheltered from sea surface agitation and gravity wave action and near enough to a robust land-based anemometer, such as that proposed, is best suited for this purpose. Once the scientific relationship between underwater noise and wind speed is determined from a stable and moored underwater sensor, sonobuoys could be used as an engineering tool for hurricane classification. A typical U.S. Navy sonobuoy such as the SSQ-57 deployed from submarine hunting aircraft could be deployed in advance of a hurricane and measure the underwater noise as the hurricane passes overhead. An empirical relationship could then be used to estimate hurricane wind speed. The SSQ-57 sonobuoy is well suited to this task and has the necessary bandwidth (10 Hz to 10 kHz) and operational life (8 hours) to make such hurricane measurements. Sonobouys are not suitable for conducting the controlled calibration experiments proposed here since it would be difficult to obtain concurrent wind speed measurements.

WORK COMPLETED AND RESULTS:

We have obtained strong experimental and theoretical evidence supporting the hypothesis that hurricanes can be accurately classified by underwater acoustic measurements [12]. On September 15, 1999 hurricane Gert passed over an underwater acoustic sensor, deployed in the North Atlantic by NOAA, which recorded the low frequency underwater noise Gert generated. Hurricanes are characterized by a low wind speed center or eye surrounded by a ring of high winds called the eye wall. As the storm passed over the acoustic sensor, two maxima in the measured noise intensity corresponding to the eye wall and a minimum corresponding to the eye were acoustically measured between 10 and 50 Hz.

Extremely accurate measurements of the wind speed structure of the hurricane were made by U.S. Air Force aircraft one day after the hurricane eye passed over the NOAA hydrophone. We advected this wind speed structure backwards in time in the direction determined by satellite imagery to hindcast wind speeds of the hurricane center as it passed over the hydrophone. We showed by regression analysis that wind speed and underwater noise intensity between 10 and 50 Hz, which is a scalar magnitude proportional to the magnitude square of the complex acoustic pressure, follow a simple power law relationship in the low frequency band of the acoustic measurements.

This follows our theory and simulations [12] which show that wind-generated noise received by a single underwater acoustic sensor in a hurricane can be well approximated by sea-surface contributions so local that wind speed and surface source intensity are effectively constant. With these findings, there is an approximately linear relationship $\log[I/1\ \mathrm{Watt/m^2\ Hz}] = n \log[V/1\ \mathrm{m/s}]+b$ between log of noise intensity I and log of local wind speed V at low frequency. The slope n of this relationship is universal and independent of measurement position, while the intercept b is a calibration that depends on local waveguide environment. The log of wind speed can be then found from measurements of ambient noise level by standard linear least squares estimation, as has been done by Shaw, Watts and Rossby [9] and Evans, Watts, Halpern and Bourassa [4] at low wind speed. The empirical fit shows that wind speed can be determined from underwater noise intensity to within a 5% error.

Before the proposed underwater acoustic technique can be used to classify hurricanes, an absolute calibration of the system is still necessary. This is due to ambiguity in the track of hurricane Gert and the need to hindcast aircraft windspeed by one day in our analysis of the data. This absolute calibration requires concurrent wind speed and ambient noise measurements such as those described in the current proposal.

After calibration, one application of the underwater acoustic technique would be to deploy multiple sonobouys, similar to those used in weather classification experiments by Nystuen and Selsor [8], from aircraft or ships in the path of an oncoming hurricane. As the hurricane passes over each sonobouy the sensor would cut a swath through the storm recording the wind speeds overhead. The swaths from multiple sonobouys should provide adequate sampling of the wind speed structure of the hurricane. This is similar to the current measurements made by hurricane-hunting aircraft which measure wind speed along swaths they cut through the storm.

The advantage of deploying sonobouys in advance of a hurricane is that the ship or aircraft never has to enter the storm and would not need to be as expensive as the specialized hurricane-hunting aircraft used today. The cost of a typical hurricane-hunting aircraft such as the WC-130 is $78 million (inflation adjusted to year 2003 dollars) [10] and the cost of a single flight [1] is roughly $155,000. Between two and eight aircraft flights are made per day [5] for potentially land-falling hurricanes in the North Atlantic where the lifespan of a hurricane can be several weeks. Twenty sonobouys, at $500 each, [7] could be deployed from inexpensive non-specialized ships or aircraft in the path of an oncoming hurricane well before conditions are dangerous for roughly $10,000. Alternatively, a hundred permanent shore-cabled hydrophone systems, at $10,000 to $20,000 each depending on cable length, could be deployed in strategic areas such as the Caribbean for roughly one million dollars.

IMPACT/APPLICATIONS:

Given the measured relationship between underwater sound and wind speed, passive acoustic intensity measurements from a single sensor can be used to estimate hurricane wind speed to within a 5% error margin and from this accurately classify the destructive power of the hurricane. This new technique has the potential to save lives and money through better hurricane classification, and from that, better hurricane forecasting.

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